UCID- 20054

HIGH-POWER RF COMPRESSOR

C. W. Hartman
J. H. Hammer
D. Meeker

March 30, 1984

Lawrence Livermore National Laboratory

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.
Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

HIGH-POWER RF COMPRESSOR

C. W. Hartman, J. H. Hammer, and D. Meeker
Lawrence Livermore National Laboratory, University of California
Livermore, CA 94550

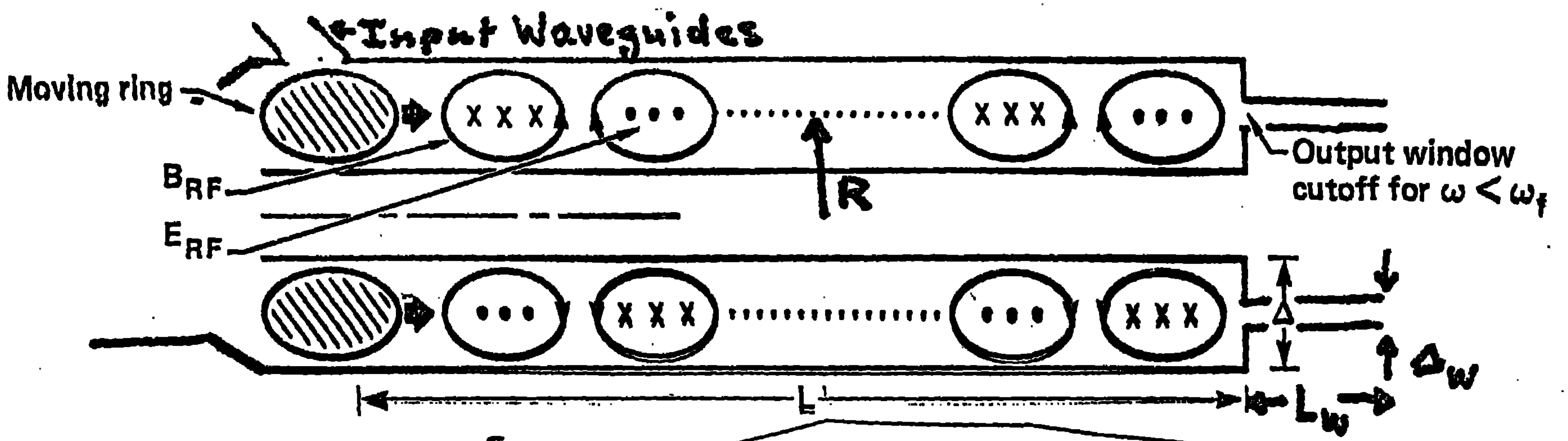
I. Introduction and Summary

We discuss here the possibility of rapidly compressing resonant RF fields in a coaxial cavity with a moving, magnetically confined plasma ring. The possibility of accelerating a plasma ring and various acceleration configurations are discussed in Ref. 1. Since the ring velocity can be high, compression to high energy density and high power can be achieved before significant resistive loss or vaporization of the cavity walls occurs. An example is given of compressing 10^5 J of λ = 15 cm stored energy to 2×10^6 J of λ = 1.0 cm RF energy with the energy released in 3 nsec for a maximum power of 6×10^{14} W. A proof of principle plasma ring accelerator experiment could provide a significant test by compressing 125 joules of 14 cm RF to 1.25 kJ of 1.4 cm radiation, released in 5 nsec for a very respectable peak power of 2.5×10^{11} W.

II. RF Compressor

The compressor considered here is shown in Fig. 1. Prior to the arrival of the moving ring at Z = L, the region 0 < Z < L is filled with TE_{01}, RF fields resonant with the mode $\frac{\omega_0^2}{c^2} = k_r^2 + k_z^2 \simeq (\frac{\pi}{\Delta})^2 + (\frac{2\pi N}{L})^2$ where the number of Z wavelengths is N. ($\Delta/R \ll 1$ where R = mean radius is assumed for simplicity.) The mode chosen (see Fig. 1) has $E = E\theta$ only, so that no electric fields terminate on conductors to avoid field emission cavity loading.

The moving ring is considered to have been accelerated by a multi-megajoule driver[2] to a velocity of order $V_r \simeq 10^9$ cm/sec, with megagauss magnetic fields, and a plasma density of $10^{17} - 10^{18}$ cm^{-3}. The ring provides a fast-moving, sliding short which compresses the cavity fields. At Z = 0 in Fig. 1, an output waveguide is located which has a cutoff frequency $\frac{\omega_{co}^2}{c^2} \simeq \left(\frac{\pi}{\Delta_w}\right)^2$ with $\omega_o \ll \omega_{co}$. As the axial length of the cavity is decreased by the moving ring, the RF resonant frequency increases as,
$\omega = c\,(\frac{\pi}{\Delta}) \left[1 + (\frac{2N\Delta}{Z})^2\right]^{1/2}$. The cavity energy increases until $\omega \simeq \omega_{co}$ at which time the compressed energy is released through the output waveguide.



$$\omega_o^2 \simeq (k_n^2 + k_z^2)\, c^2, \quad k_n \approx \frac{\pi}{\Delta}$$

$$\left.\begin{aligned} \frac{\omega}{\omega_o} &\simeq \frac{L_o}{L} \\ \frac{U_{rf}}{U_{rfo}} &= \frac{L_o}{L} \end{aligned}\right\} \text{Compression laws - no losses}$$

Fig. 1. Compression of R.F. cavity modes.

To estimate the compression and release of the RF energy, we neglect losses so that the time variation of the RF energy is given by,

$$\frac{dU_{rf}}{dt} = 2\pi R\Delta \frac{B_{rf}^2}{2\mu_o} V_r - \frac{B_{rf}^2}{2\mu_o} c\ 2\pi R\Delta_w \exp\left\{- 2 \left[\left(\frac{\pi}{\Delta_w}\right)^2 - \frac{\omega^2}{c^2}\right]^{1/2} L_w\right\} \qquad (1)$$

where the first r.h.s. term gives the increase of U_{rf} by compression and the second gives the evanescent transmission of power through the cutoff waveguide. Equation (1) can be written,

$$\dot{U}_{rf} = - U_{rf} \frac{\dot{Z}}{Z} - U_{rf} \frac{c}{Z}\frac{\Delta_w}{\Delta} \exp\left\{- 2 \left[\left(\frac{\pi}{\Delta_w}\right)^2 - \frac{\omega^2}{c^2}\right]^{1/2} L_w\right\} \qquad (2)$$

where $Z = - V_r$. The second r.h.s. term is negligible until $\omega \simeq \omega_{co}$ or, $Z = Z_{co} = 2N\Delta_w$, provided $\frac{2\pi L_w}{\Delta_w} >> 1$ as we would choose. With negligible transmission through the output waveguide the RF energy increases as $U_{rf} = U_o \frac{L}{Z}$ from Eq. (2). When $\omega \simeq \omega_{co}$ the second term of Eq. (2) becomes dominant.

The risetime for the transmitted power may be roughly estimated by calculating the time required for the exponent in Eq. (2) to change from 1 to 0. For exp = 1, $\left(\frac{\pi}{\Delta_w}\right)^2 - \frac{\omega^2}{c^2} = \frac{1}{4\ L_w^2}$. The term $\frac{1}{4\ L_w^2}$ is small, and $\omega \simeq \omega_{co} = \frac{\pi c}{\Delta_w}$.

Letting $\omega = \omega_{co} - \Delta\omega$ where $\Delta\omega$ is the frequency shift for exp = 1, gives $\Delta\omega = \frac{c^2}{8\ L_w^2 \omega_{co}}$. Setting $\Delta\omega = \dot{\omega}\tau_{rise}$ where, $\dot{\omega} \simeq \omega_{co} \frac{V_r}{Z_{co}}$ gives $\tau_{rise} = \frac{c^2 Z_{co}}{8\ L_w^2 \omega_{co}^2\ V_r} = \frac{N\ \Delta_w^3}{4\pi^2 L_w^2\ V_r}$. If τ_{rise} is shorter than the light transit time for the cutoff waveguide, L_w/c, then $\tau_{rise} = L_w/c$ should be used. Once the cutoff frequency is exceeded, the RF power transmitted through the guide exceeds the compression term by $c\Delta_w/V_r\Delta > 1$. The RF field then decays from Eq. (2) as,

$$\dot{U}_{rf} \simeq - U_{rf} \frac{c}{Z_{co}} \frac{\Delta_w}{\Delta} \tag{3}$$

i.e., with a time constant $\tau_{decay} \simeq \frac{Z_{co}}{c} \frac{\Delta}{\Delta_w}$. The maximum stored U_{rf} is $U_{max} = U_o \frac{L}{Z_{co}}$ and the maximum power is, $P_{max} = \frac{U_o L}{Z_{co}} \frac{c}{Z_{co}} (\frac{\Delta_w}{\Delta})$. The output is shown in Fig. 2.

As an example, we consider an initial cavity length L = 100 cm with Δ = 10 cm, and $N = \frac{L}{2\Delta}$ = 5 wavelengths in the z-direction. The initial resonant frequency is f = 2000 Hz (λ_0 = 15 cm). Prior to the ring's arrival, a 2 μsec pulse of 50 GW power is used to establish 100 kJ of stored RF energy in the cavity. The ring compresses the RF field energy 20-fold at 10^9 cm/sec until $\lambda = \lambda_{co}$ (taken here to be λ_{co} = 1.0 cm). At $Z = Z_{co}$ = 5 cm, U_{rf} has increased to 2 MJ and the output waveguide begins to transmit. The power rises in $\tau_{rise} = \frac{L_w}{c} \simeq$ .15 nsec to $P_{max} = 6 \times 10^{14}$ watts and decays with a time constant τ_{decay} = 3 nsec.

Appendix A discusses a similar example of RF compression by a lower energy ring as might be produced in a proof of principle experiment.

III. Loss

Next, consider losses, first in the cavity walls and then in the ring. Since, the electrical skin depth $\delta = \sqrt{\frac{\eta}{\omega\mu_o}}$ is less than the thermal skin depth, $\delta_{th} = \sqrt{\frac{\kappa}{C\tau}}$ for $\omega\tau >> 1$, the surface temperature of the cavity walls during filling is,

$$T_s = \frac{4}{3\sqrt{\pi}} \frac{P_o}{t_o} \frac{t^{3/2}}{\sqrt{C\kappa}} \tag{4}$$

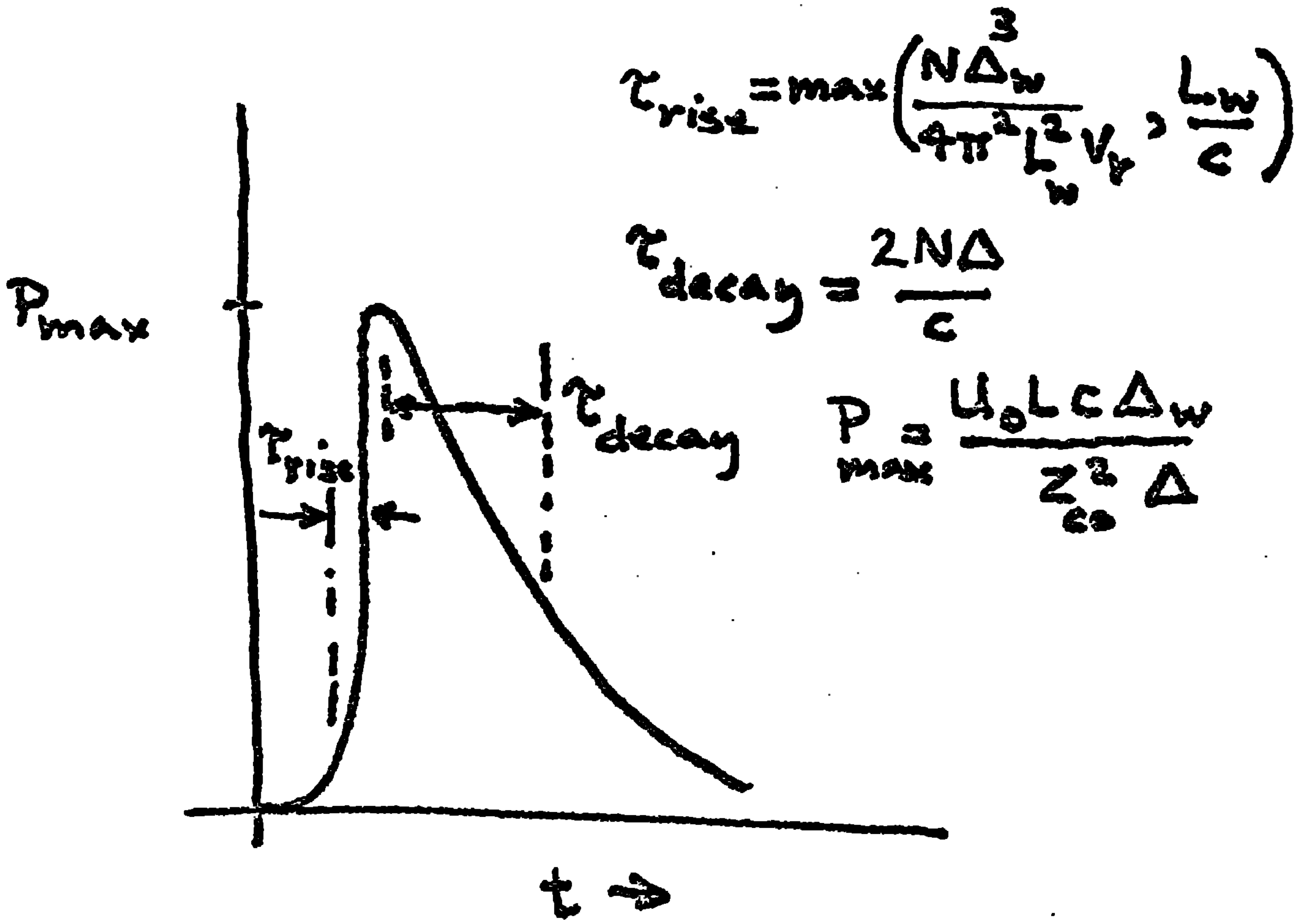


Figure 2. P_{rf} vs time.

where the power incident on the walls is $P_{walls} \simeq \omega \frac{B_{rf}^2}{2\mu_o} \delta = P_o \frac{t}{t_o}$ watts/cm^2

(a linear time dependence of the incident power is used for simplicity).

For the example considered in Section II (100 kJ RF at $\lambda = 15$ cm, $L = 100$ cm, $\Delta = 10$ cm and $R = 10$ cm, $B_{rf\ max} \simeq 20$ kG), $\delta = 10^{-4}$ cm, and $P_o = 2 \times 10^4$ w/cm^2. Setting $t = t_o$ in Eq. (4) gives a temperature rise $T_s \simeq 1000^oC$.

During compression by the ring, $U_{rf} \propto Z^{-1}$ and $\omega \propto \frac{1}{Z}$ giving $P_{walls} \propto B_{rf}^2 \delta\omega \sim \frac{U_{rf}}{Z} \omega^{1/2} \sim \frac{1}{Z^{5/2}}$ so that the wall power rises very rapidly as $Z \to Z_{co}$.

At $Z = Z_{co} = 5$ cm, $U_{rf\ max} = 2 \times 10^6$ j, $B_{rf} = 400$ kG, and $P_o = 3 \times 10^9$ w/cm^2. Taking the characteristic time for power rise t_o to be $\frac{Z_{co}}{V_r} \simeq 5$ nsec, the energy investment in the wall surface from Eq. (4) is $CT_s = 2. \times 10^5$ j/cm^3. This energy density corresponds to about 3 eV per atom, i.e., sufficient for vaporization of the surface. The total energy lost in the walls is about 40 kJ or 2% of the RF energy. Additional losses due to vaporization may occur, however, it is useful to observe that at 1 eV a copper atom can move only 10^{-3} cm in the final 5 nsec of compression.

RF losses in the ring are too difficult to evaluate in detail in this preliminary note. We observe that the induced currents are azimuthal so that electrode sheaths should not be important. In order to compress to $B_{rf} \simeq 400$ kG, it appears likely that the ring field should be about as large as B_{rf}. Taking $B_{ring} = 500$ kG as an example, the electron/ion cyclotron frequencies are $f_{ce}/f_{ci} = 1.5 \times 10^{12}/4 \times 10^8$ Hz for hydrogen while the RF frequency ranges from $.2 - 3 \times 10^{10}$ Hz. Gyroresonances in the main ring region are therefore not expected. The plasma density of the ring might be $n_e \simeq 10^{17}$ cm^{-3} which is well beyond cutoff, even at the highest RF frequency ($n_{comax} \simeq 10^{13}$ cm^{-3}).

In the absence of turbulence the RF current tends to flow in a small thickness skin. At $n_e = 10^{17}$ cm^{-3}, the collision-free skin depth is small, $\delta_{cf} \simeq 2 \times 10^{-3}$ cm, and at surface currents $I' \simeq .4$ MA/cm the drift speed required $v_D = \frac{I'}{n_e \delta_{cf} e}$ is $v_D \simeq 10^{10}$ cm/sec ($E = 30$ keV drift energy). Instabilities will tend to heat and broaden the layer. Taking a broadened skin depth $\delta \simeq 10\ \delta_{cf} \simeq 2 \times 10^{-2}$ cm, gives $E_D \simeq 300$ eV. Even if the full RF energy is deposited in width δ each radian the total losses during the final compression time $\tau = 5$ ns would be roughly $\frac{B_{rf}^2}{2\ \mu_o} \tau\ \omega\ \delta\ 2\pi R\Delta \simeq 10^5$ joules or 5% of U_{rf} max.

APPENDIX A. PROOF OF PRINCIPLE RF COMPRESSOR

We have considered a high-energy RF compressor which would use a corresponding high energy ring such as might be obtained using the Shiva-Star 9.3 MJ bank. Here we consider an RF compression test using a moving ring having parameters approximating those which might be achieved in the proof of principle experiment.

Under typical conditions we would expect to produce in the POP experiment a ring having the parameters shown in Fig. 3.

As in the high energy case, we consider a coaxial cavity (Fig. 1) 100 cm long prefilled with 125 J of a λ_0 = 14 cm cavity mode having N = 7 wavelengths in the z direction. The output waveguide has a cutoff wavelength λ_f = 1.4 cm corresponding to a 10-fold compression of the RF energy to 1.25 KJ before transmission. At final compression (L_f = 10 cm) the RF field has increased to B_{rf} = 5 kG, or roughly 1/2 of the ring field.

When $\omega_{rf} > \omega_{co}$ ($\lambda_f \simeq 1.4$ cm the transmitted power increases to

$$P_{max} \simeq U_{rf\ max} \frac{\Delta_w}{\Delta} \frac{c}{L_f} \simeq 250 \text{ G watt}$$ and decays with a time constant τ = 5 nsec.

The temperature rise of the RF cavity walls is predicted to be modest (< 100°C) for this case. A test at this, not insignificant, power level would provide information on RF losses in the ring at $B_{rf} \simeq 1/2\ B_{ring}$.

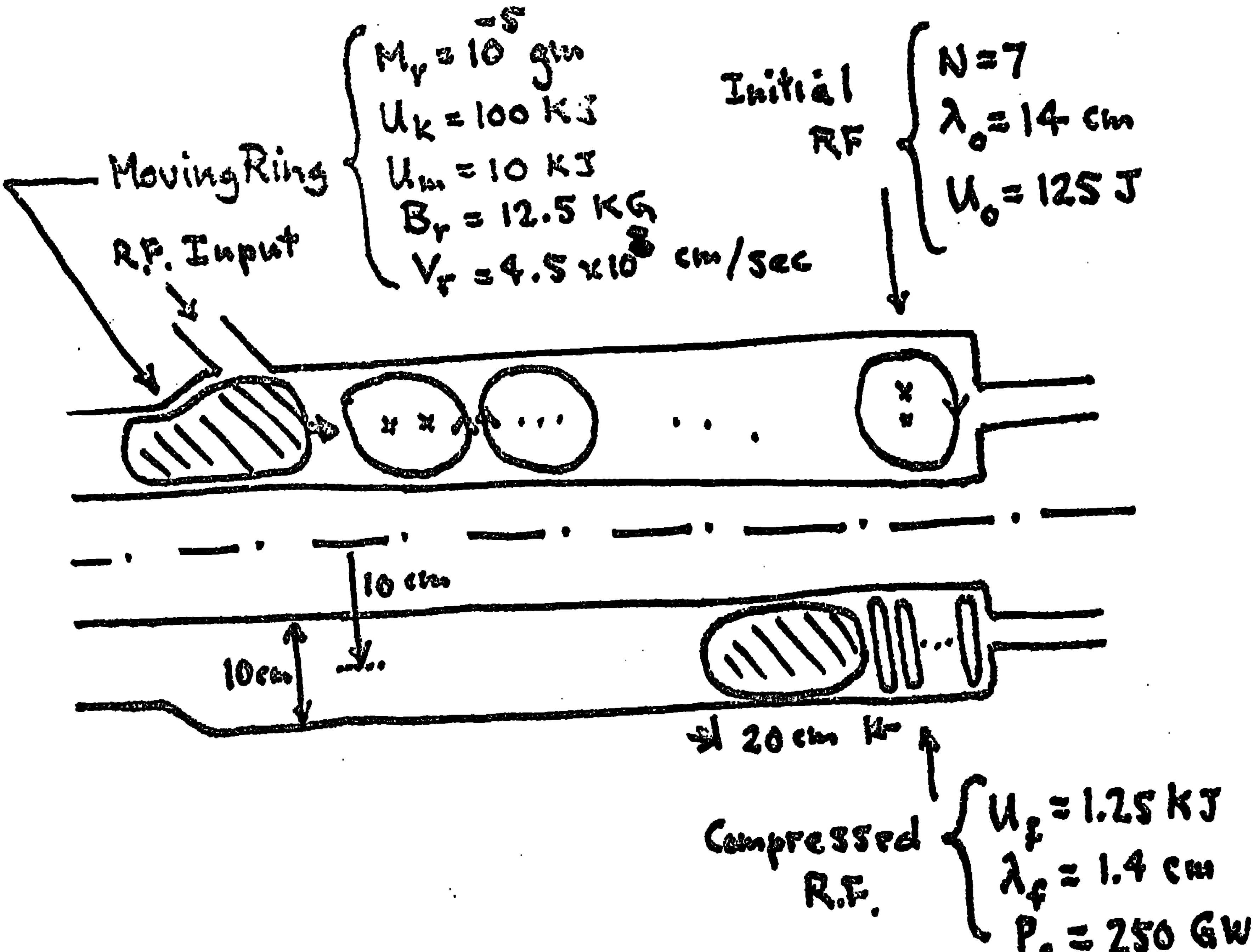


Fig. 3. Proof of principle compressor.

REFERENCES

1. C. W. Hartman and J. H. Hammer, Phys. Rev. Lett. 48 (1982) 929.
2. C. W. Hartman et al., Proceedings of the Fifth Symposium on The Physics and Technology of Compact Toroids, Nov. 16-18, 1982.

5838r/0498r/CWH/jdb
3/20/84